FUTURE EUV OBSERVATIONS OF THE INTERSTELLAR MEDIUM
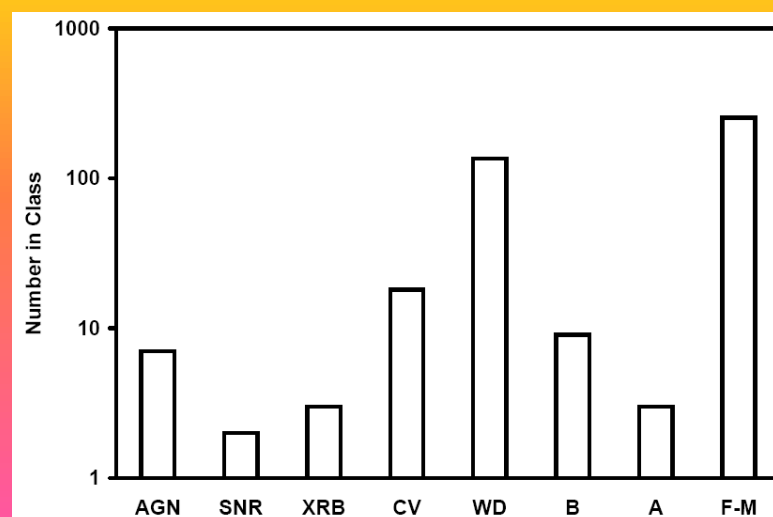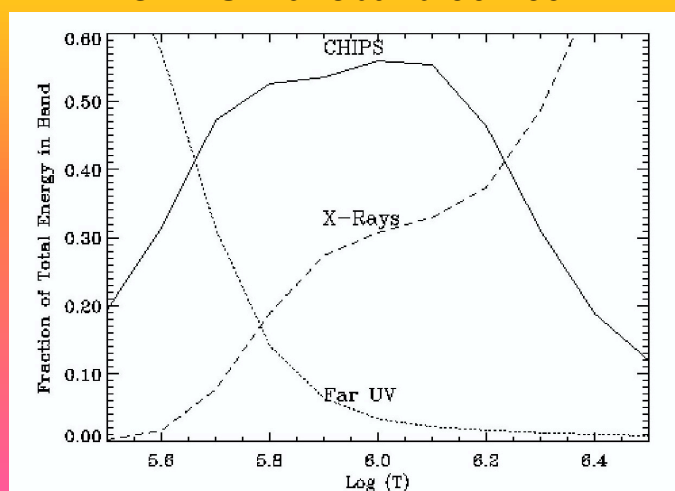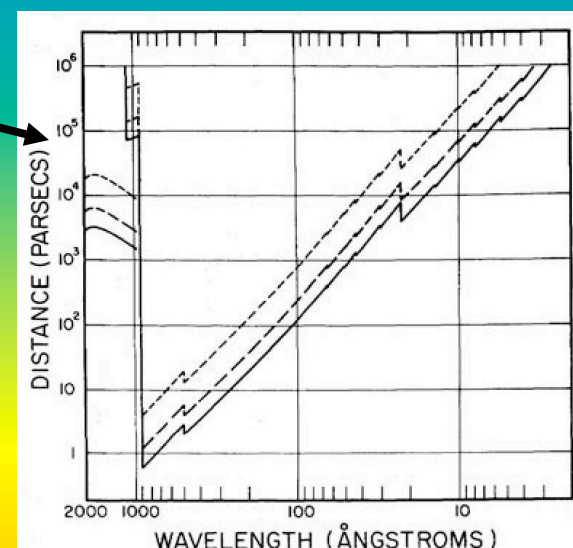
M. P. Kowalski (NRL), K. S. Wood (NRL), M. A. Barstow (U. Leicester), R. G. Cruddace (NRL)
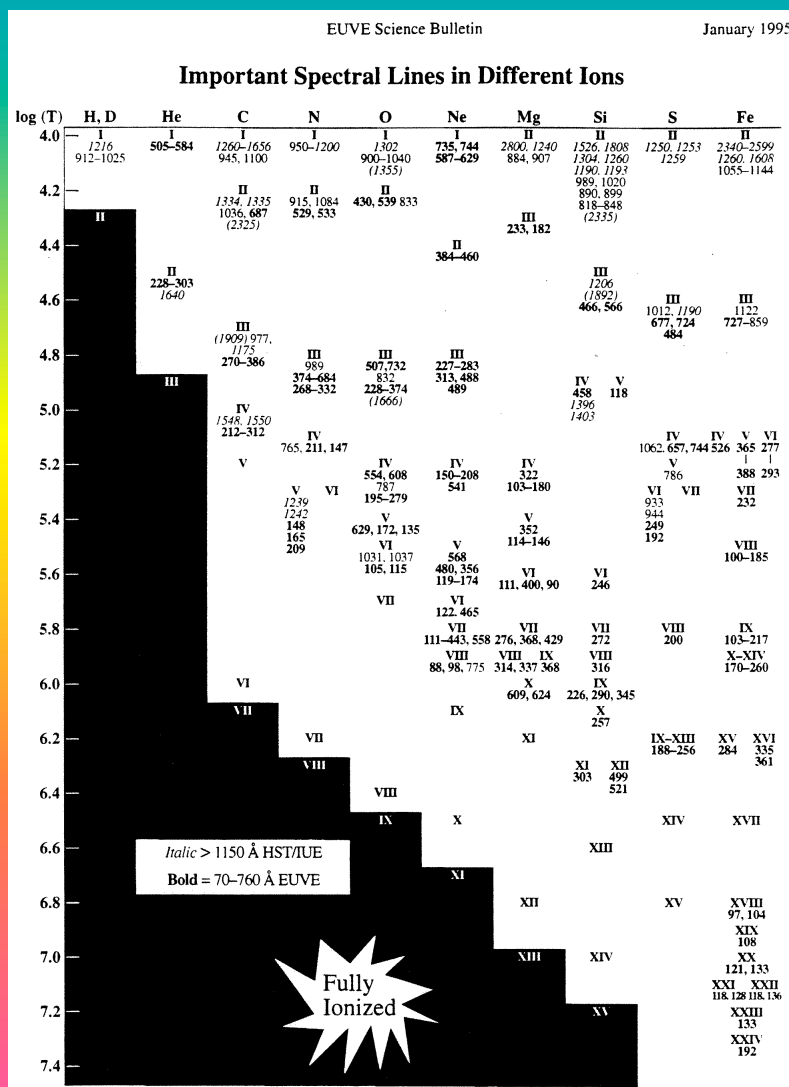
WHY LOOK IN THE EUV?

- **Operating Regime ~50-350 Å (soft X-ray/EUV)**
  - **Interstellar Medium (ISM) opacity low ~100 pc, patchy**
    - **Extragalactic for <120 Å**
  - **Absorption features diagnose ISM***
- **WFC, *EUVE* catalogs: ~1100 EUV sources**
  - **Statistics, Probe ISM structure, Timing**
  - **Most numerous: stellar coronae, white dwarfs**
  - **All other source classes represented**
  - **Unexpected: B stars, AGNs, clusters of galaxies**
- **Bulk of emission of 10^6 K plasmas in EUV**
 - ***CHIPS* Waveband 90-260 Å**

EUV SPECTROCOPY: LINES

Important Spectral Lines in Different Ions

log (T)	H, D	He	C	N	O	Ne	Mg	Si	S	Fe
4.0	I *1216* *912–1025*	I **505–584**	I *1260–1656* *945, 1100*	I *950–1200*	I *1302* *900–1040 (1355)*	I **735, 744** **587–629**	I *2800, 1240* *884, 907*	II *1526, 1808* *1304, 1260 1190, 1193 989, 1020 890, 899 818–848 (2335)*	II *1250, 1253* *1259*	II *2340–2599* *1260, 1608 1055–1144*
4.2			II *1334, 1335* *1036, 687 (2325)*	II *915, 1084* **529, 533**	II *430, 539 833*		III *233, 182*			
4.4	II					II *384–460*				
4.6		II **228–303** *1640*						III *1206 (1892)* **466, 566**	III *1012, 1190* **677, 724** *484*	III *1122* *727–859*
4.8		III	III *(1909) 977, 1175* **270–386**	III *989* *374–684* **268–332**	III *507, 732* *832* **228–374** *(1666)*	III *227–283* **313, 488** *489*				
5.0			IV *1548, 1550* **212–312**					IV *1062, 657, 744* **526**	V **365**	VI **277**
5.2			V	IV *765, 211, 147*	IV *554, 608* *787* **195–279**	IV *150–208* **541**	IV *322* **103–180**	IV **786**	VI **388** VII **933 944 249 192**	VII **293** VII **232**
5.4			VI *1239 1242 148 165 209*	V *629, 172, 135*	V *1031, 1037* **105, 115**	V *352* **114–146**		VI **933 944 249 192**		
5.6					VI **480, 356** **119–174**	V **568**	VI **111, 400, 90**	VI **246**		VIII **100–185**
5.8			VI *122, 465*		VII **111–443, 558**	VI VII **276, 368, 429**	VII **272**	VIII **200**		IX **103–217** X–XIV **170–260**
6.0		VI	VII	VII	VIII **88, 98, 775**	VIII IX **314, 337 368**	X **609, 624**	IX **226, 290, 345**		
6.2			VII		IX	X **257**	XI	IX–XIII **188–256**	XV **284**	XVI **335 361**
6.4		VII	VIII	VIII			XI XII **303** **499 521**	XIV	XVII	
6.6				VII	IX	X		XIII		
6.8						XI	XII	XV	XVIII **97, 104** XIX **108**
7.0				XII		XIII	XIV		XX **121, 133**
7.2					XIII	XIV		XV	XXI XXII **118, 128 118, 136** XXIII **133**
7.4									XXIV **192**

Italic > 1150 Å HST/IUE
Bold = 70–760 Å EUVE

Fully Ionized

- **Wealth of Lines (left)**
  - **Span 0.1×10^6 to 20×10^6 K**
  - **All cosmologically interesting elements**
    - **H, He, C, N, O, Ne, Mg, Si, S, Fe**
  - **Broad Ionization range**
    - **e.g., Fe III – XXIV**
    - **mostly L-shell**
    - **complements X-ray K-shell**
- **Critical Diagnostics Not found at other λ**
  - **e.g., bound-free continuum of He II (<228 Å) and Ly series (228-304 Å) are ONLY useful diagnostics of ISM He II density**

MULTILAYER COATINGS:
TECHNICAL KEY TO HIGH EUV SENSITIVITY

- **Alternating layers of absorbing and transmitting materials**
- **Function as synthetic Bragg crystals**
- **At near-normal incidence**
  - **EUV reflectance enhanced 100x or more: 70% reflectance achieved**
  - **Avoid aberrations associated with grazing incidence: Low instrument size, weight, cost**
- **Fabrication Mature ("atomic engineering")**
 - **Magnetron Sputtering, Thermal Evaporation**
  - **Accurate Modeling Codes**

λ

θ

D

Substrate

SEM Photo of Mo /Si Multilayer

Measured

Calculated
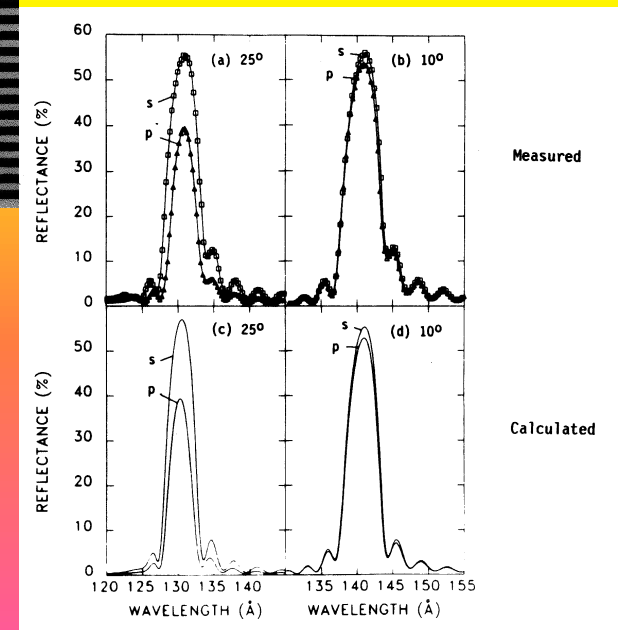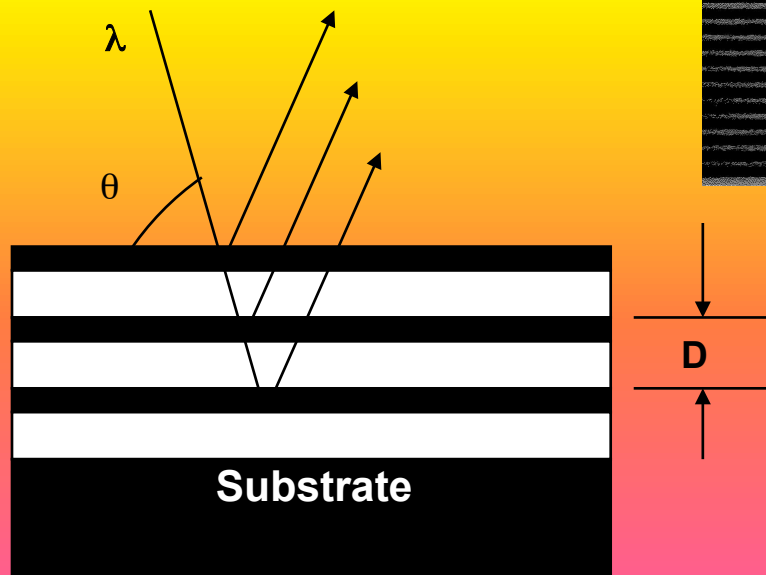
MULTILAYER GRATING DESIGNS

- **Obeys Grating Equation: $m\lambda = d\,(\sin\alpha \pm \sin\beta)$**
- **Spectral Resolution unaffected**
  - **Diffraction-limited R~14,000 obtained**
- **Measured Efficiency = Multilayer Reflectance x Groove Efficiency**
- **Theoretical Maximum Groove Efficiency**
  - **40.5% Laminar groove profile (right) in 1st order only**
  - **~100% Blazed groove profile (left) in order of choice**
- **Fabrication Techniques Mature**
  - **Best: Holographic Ion-etched Gratings**
    - **Accurate Groove Profile**
    - **Smooth Surface**
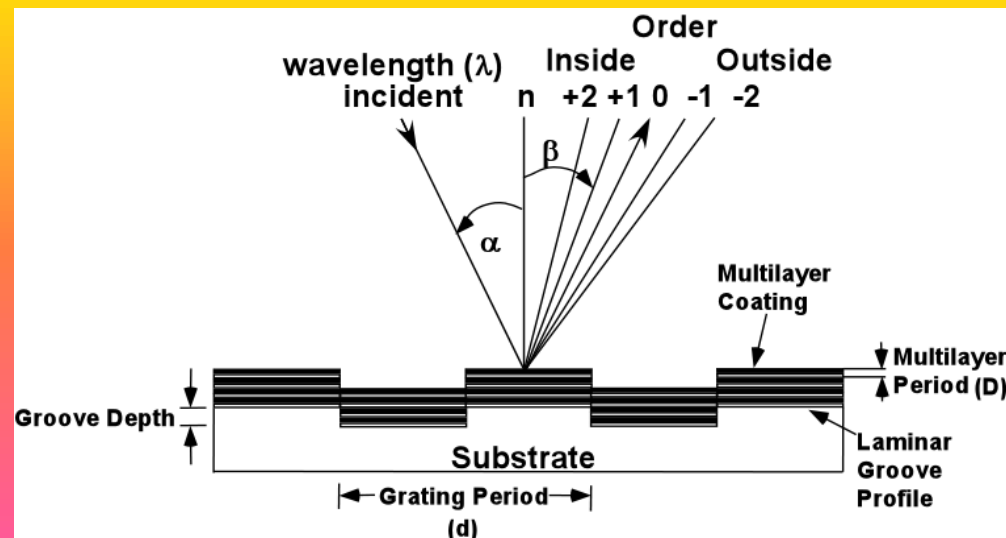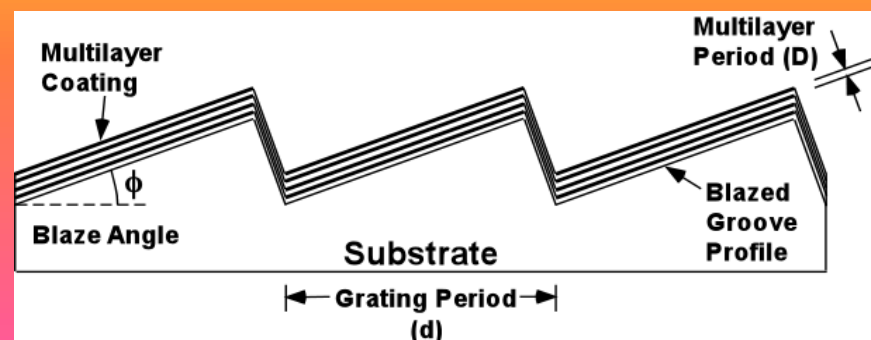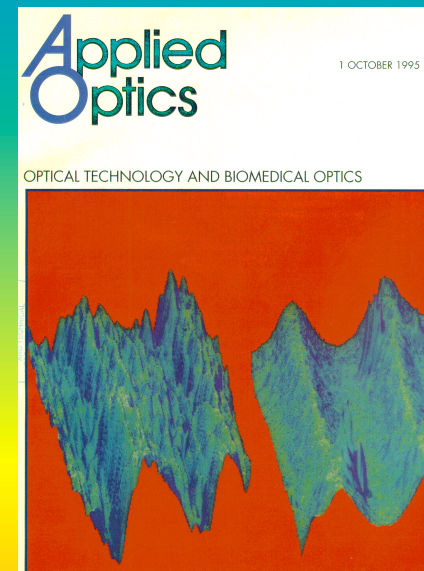
MATURE TECHNOLOGY

- **Computational Models**
  - Design grating or mirror substrate
  - Design multilayer-coating with high reflectance in waveband of interest
- **Uncoated substrate procured commercially (e.g., Zeiss)**
  - Surface characteristics obtained using atomic force microscope (AFM)
  - Optical performance determined using synchrotron radiation
- **Multilayer coating applied to substrate and witness flat**
  - Troy Barbee, LLNL (world expert)
- **Repeat performance measurements on multilayer-coated optic**
- **Multilayer-coated optic mounted in instrument**
  - Determination of spatial or spectral resolution
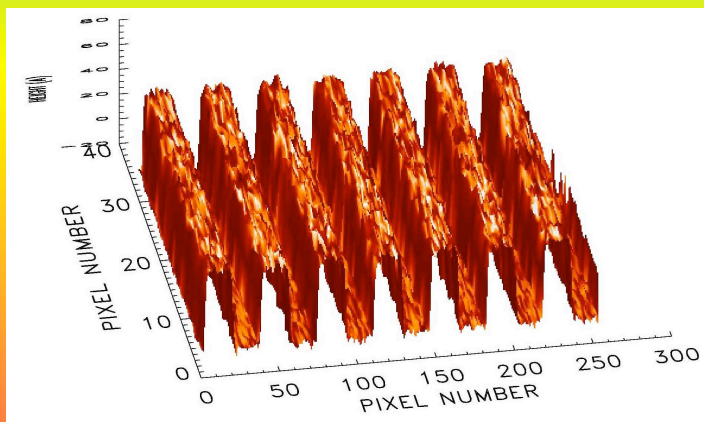 - Flight

Fig 1: Explorer Head
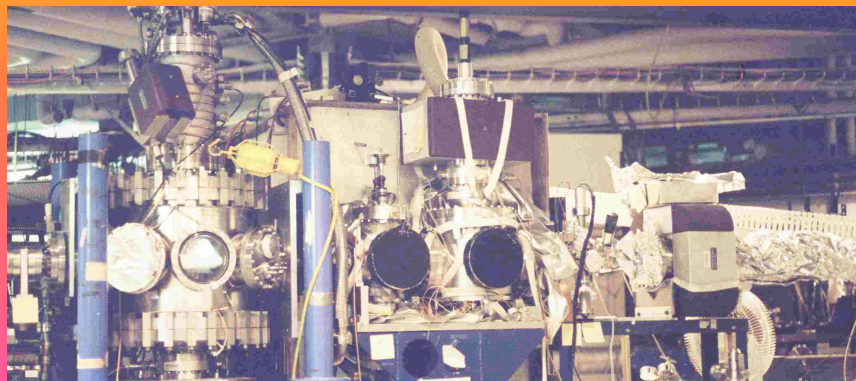
- National Synchrotron Light Source, Brookhaven National Laboratory
- NRL Beamline X-24C

# J-PEX SOUNDING ROCKET PAYLOAD: GRATINGS

- **4 Identical Holographic Ion-Etched Laminar Multilayer Gratings**
  - **Each 16x9 cm (bottom), 3600 grooves/mm, fabricated at Zeiss**
  - **Very smooth: AFM roughness 3-4 Å rms (left)**
  - **Measured efficiency: 10.3% (right)**
  - **Groove efficiency: 34% (40.5% theoretical max)**
  - **Uniformity: 6% across surface**
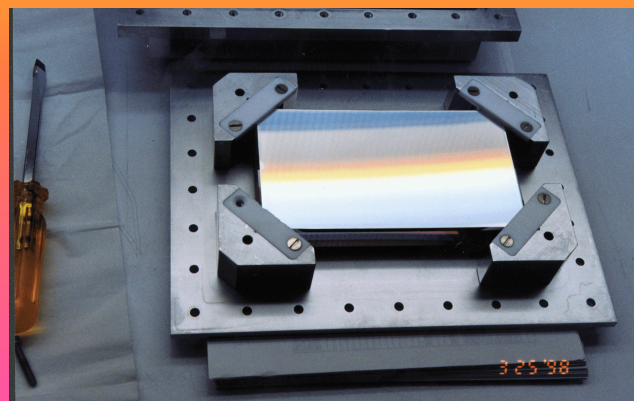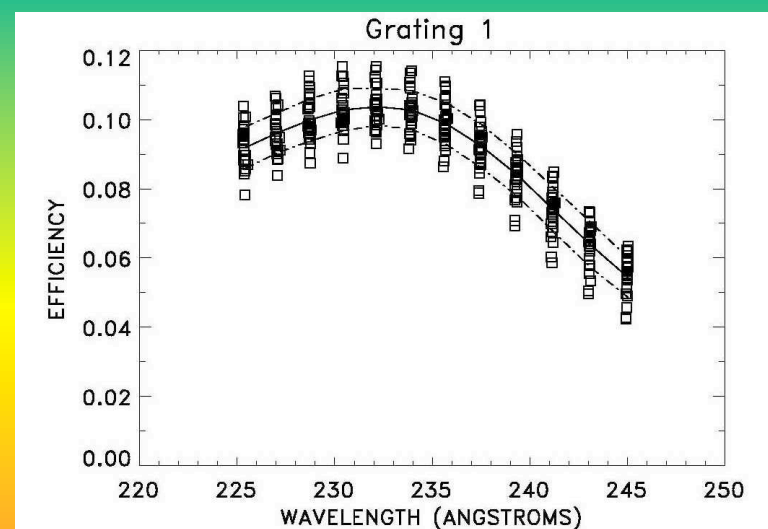
J-PEX FLIGHT 36.195

- **21 February 2001 9:55 pm MST: WSMR (left)**
  - **Near perfect flight with 300 seconds on target**
  - **EUV Multilayer Grating Spectrometer: Resolution ~3,000, Effective Area ~3 cm^2**
  - **Raw data image (right): 4 spectra, 3 detector calibration points, EUV image**
  - **First Successful High-Resolution EUV spectrum of an Astrophysical Object**
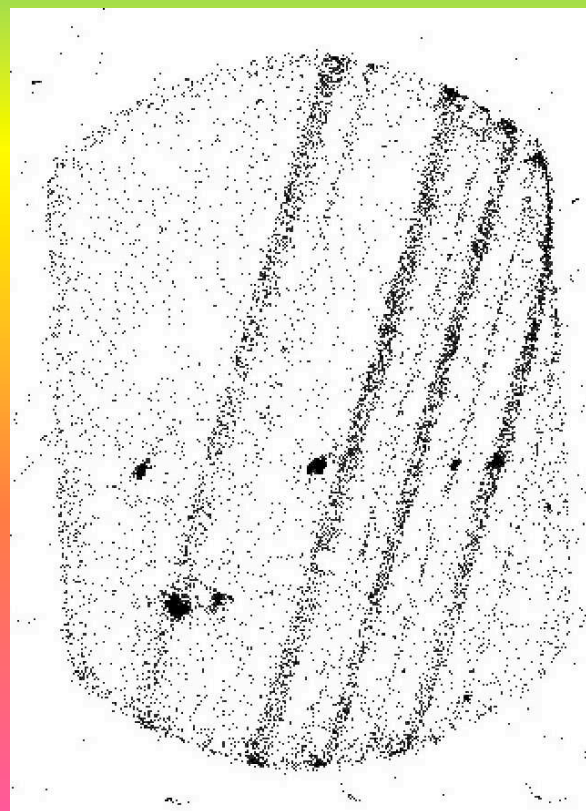
J-PEX SCIENCE GOALS

- **Motivation**
  - WD endpoint of stellar evolution: 90% of all stars in galaxy
    - Enrich ISM
    - Possible progenitors of SNe Ia (CVs)
  - Two cooling sequences for WD observed on H-R diagram
    - DA (hydrogen rich)
    - DO and DB (helium rich)
      - Gap in evolution path (T_{eff}) taken as evidence for temporary migration to DA path
  - Detection of He in DA supports migration theory
    - EUV most sensitive region, requires high resolution
    - Models
      - Homogeneous
      - Stratified
        - Levitation
        - Diffusion

- **Goals**
  - Detect He in photosphere of DA WD G191-B2B
  - Determine amount of ISM He II
  - Record absorption lines of heavier elements (C, N, O, Fe)

M. A. Barstow
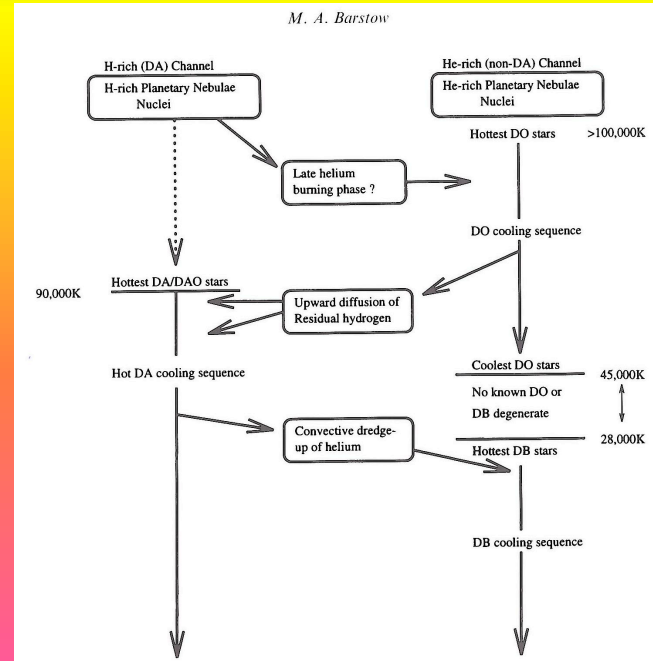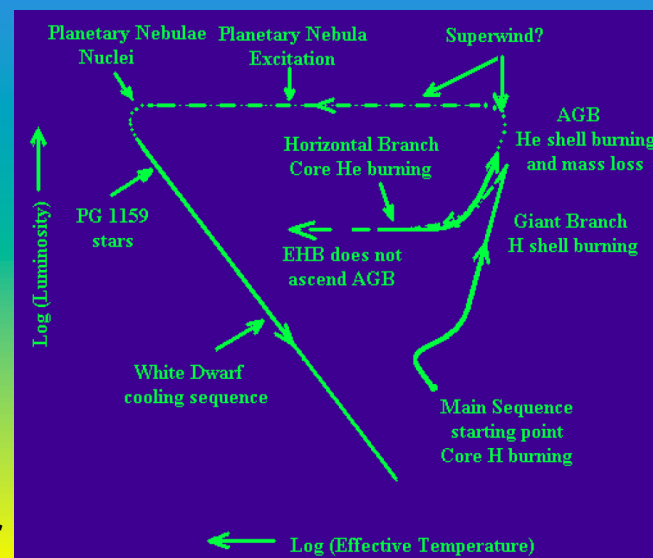
J-PEX SPECTRUM RESULTS

- **Final Result**
  - Data (black) and best-fit model (red) of photosphere+ISM: good agreement
  - Cluster of O IV lines @ 233.5 Å detected
  - Broad feature 227-232 Å characteristic of overlapping ISM He II lines on continuum at series limit
  - No significant detection of He II photosphere lines, e.g.,@ 243.026 Å or 237.331 Å, BUT…

- **Initial Modeling**
  - Homogeneous composition
  - T_{eff} = 54,000 K, log g = 7.5, non-LTE code TLUSTY, use XSPEC with *J-PEX* response
  - Fixed: H I (ISM)=2.15×10^{18} cm^{-2}, He I (ISM)=2.18×10^{17} cm^{-2}, photosphere heavy element abundances
  - Best-fit (99%): $N_{He\ II}$(ISM) = 5.97 (5.76-6.18) $\times 10^{17}$ cm^{-2}, n_{He}(photosphere) = 1.60 (1.31-1.91) $\times 10^{-5}$ cm^{-2}
  - Indirect detection of photospheric He
  - High Ionization Fraction (~0.73) compared to Local ISM (0.25-0.50)

- **Further Modeling**
  - Stratified models do not produce better fit
  - Additional ISM component (Local Interstellar Cloud) lowers Ionization Fraction (consistent w
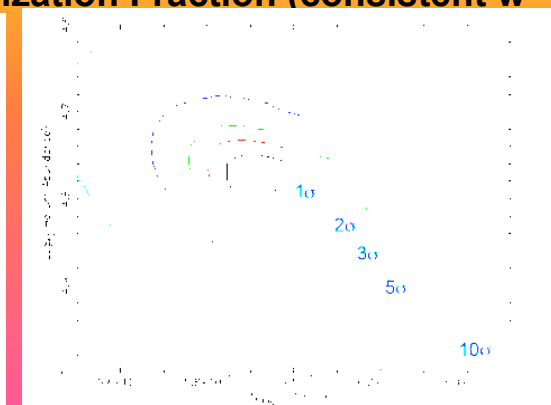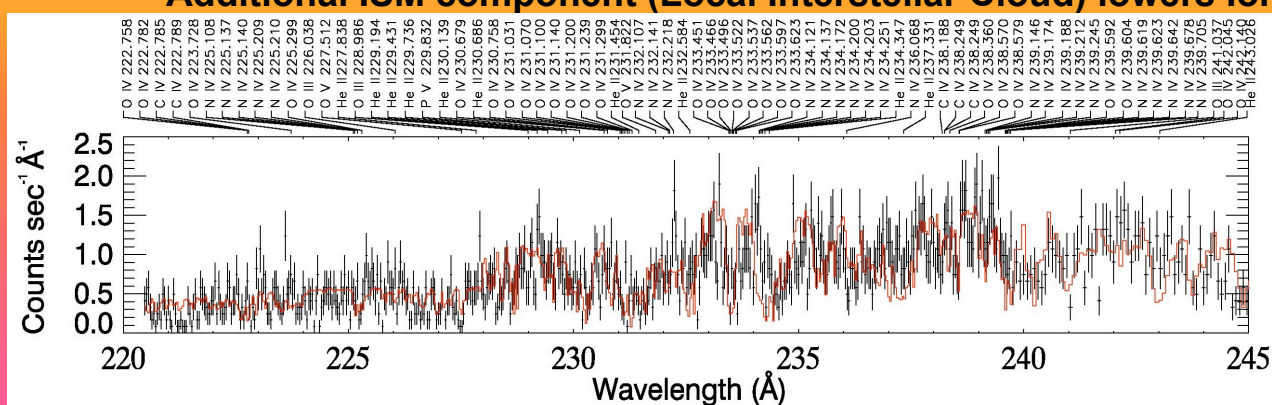
J-PEX APPROVED REFLIGHT

- **Technical Improvements**
  - **Replace Spherical Laminar Gratings with Parabolic Blazed Gratings**
    - **Smooth and near-ideal groove profile**
      - **50% Groove Efficiency (Previous 27%)**
    - **Parabolic figure reduces grating aberrations**
  - **New grating mounting eliminates grating stress**
  - **New Microchannel Plate Detector**
    - **KBr photocathode achieves 22% quantum efficiency (Previous 14%)**
    - **High resolution crossed grid anode achieves 18 micron spatial resolution**
  - **New rocket booster provides 25% increase in observation time**
- **Net Performance Increase from Technical Improvements**
  - **7 cm^2 Effective Area x 380 sec: x4 improvement in sensitivity**
  - **Spectral resolution 3500-5100: 50% improvement**
- **Launch: 2 Oct 2008**
- **Target: White Dwarf Feige 24**

- **Science Goals**
  - **Unambiguous detection of photospheric He (243.026 Å): more likely**
    - **Measure at quadrature**
    - **Distinguish ISM and photospheric components**
  - **Investigate Common Envelope evolution in binary White Dwarf system**
  - **Measure H I layer mass**
  - **Test accuracy of atomic data and reliability of atomic data calculations (millions of lines)**
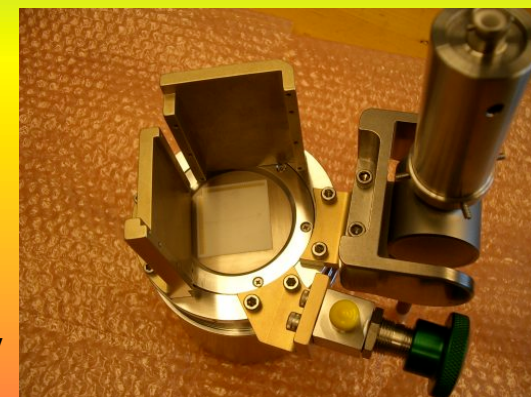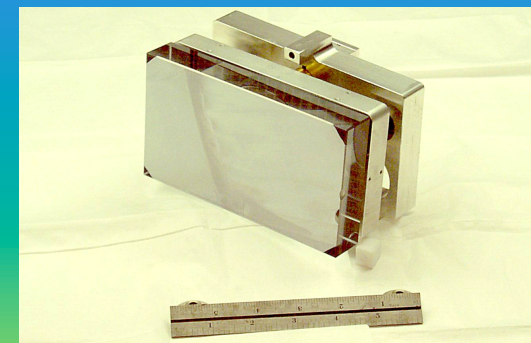
FUTURE: J-PEXsat

- **New low-cost launch vehicles create opportunities for sounding rocket payloads into orbit**
  - Left: SpaceX Falcon 1 (2-stage liquid-propellent)
  - Right: ATK (Thiokol) development of ALV (3-stage solid-propellent)

First Falcon 1 static firing at Vandenberg
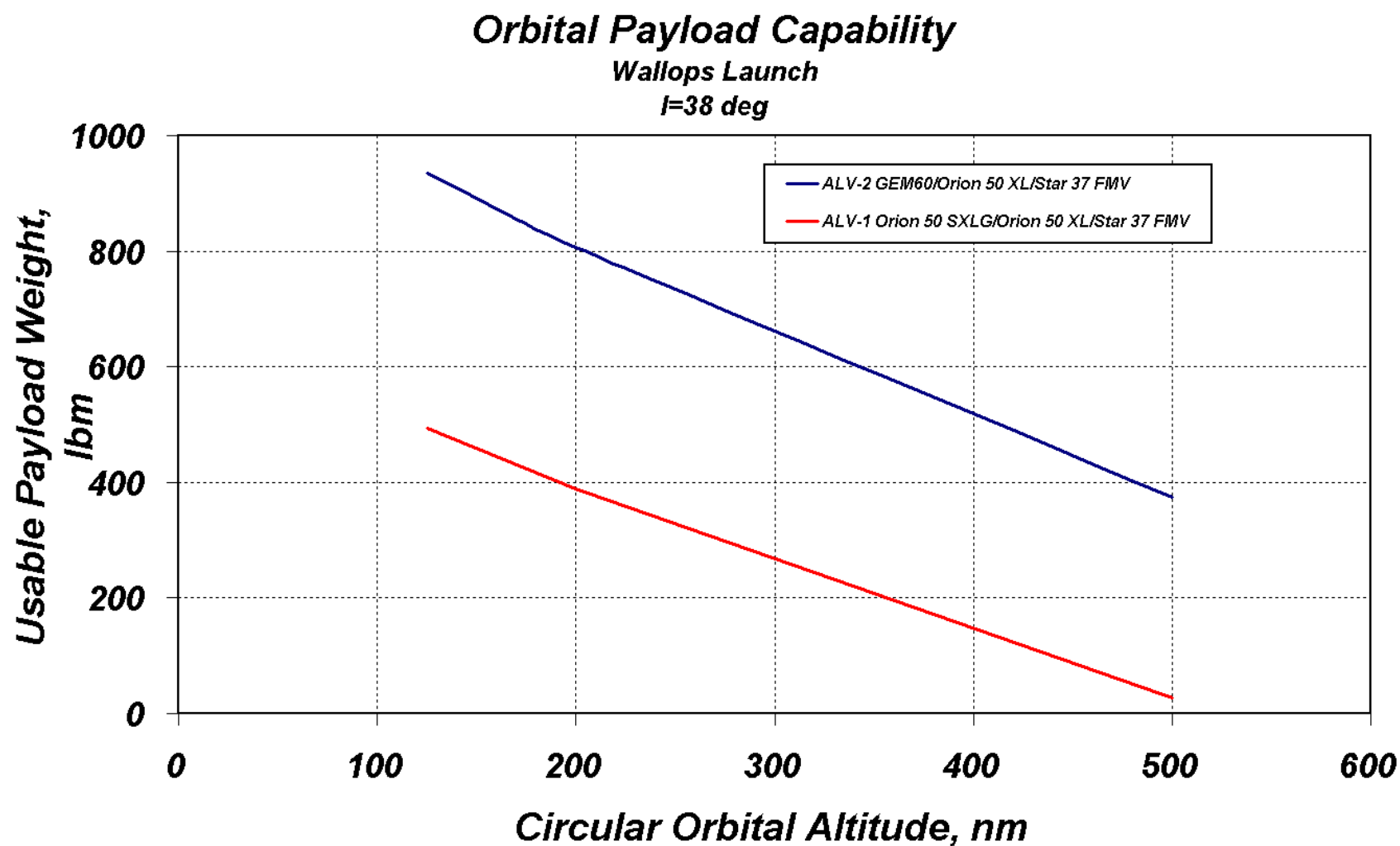

Falcon 1 on launch pad at Kwajalein

Flight test of ASAS™ 21-120 rocket motor

Orbital Payload Capability
Wallops Launch
I=38 deg

Legend:
- ALV-2 GEM60/Orion 50 XL/Star 37 FMV
- ALV-1 Orion 50 SXLG/Orion 50 XL/Star 37 FMV

VEHICLE CONFIGURATION ALV 2

50-in. Fairing

STAR™ 37FMV

Orion 50 XL

GEM 60
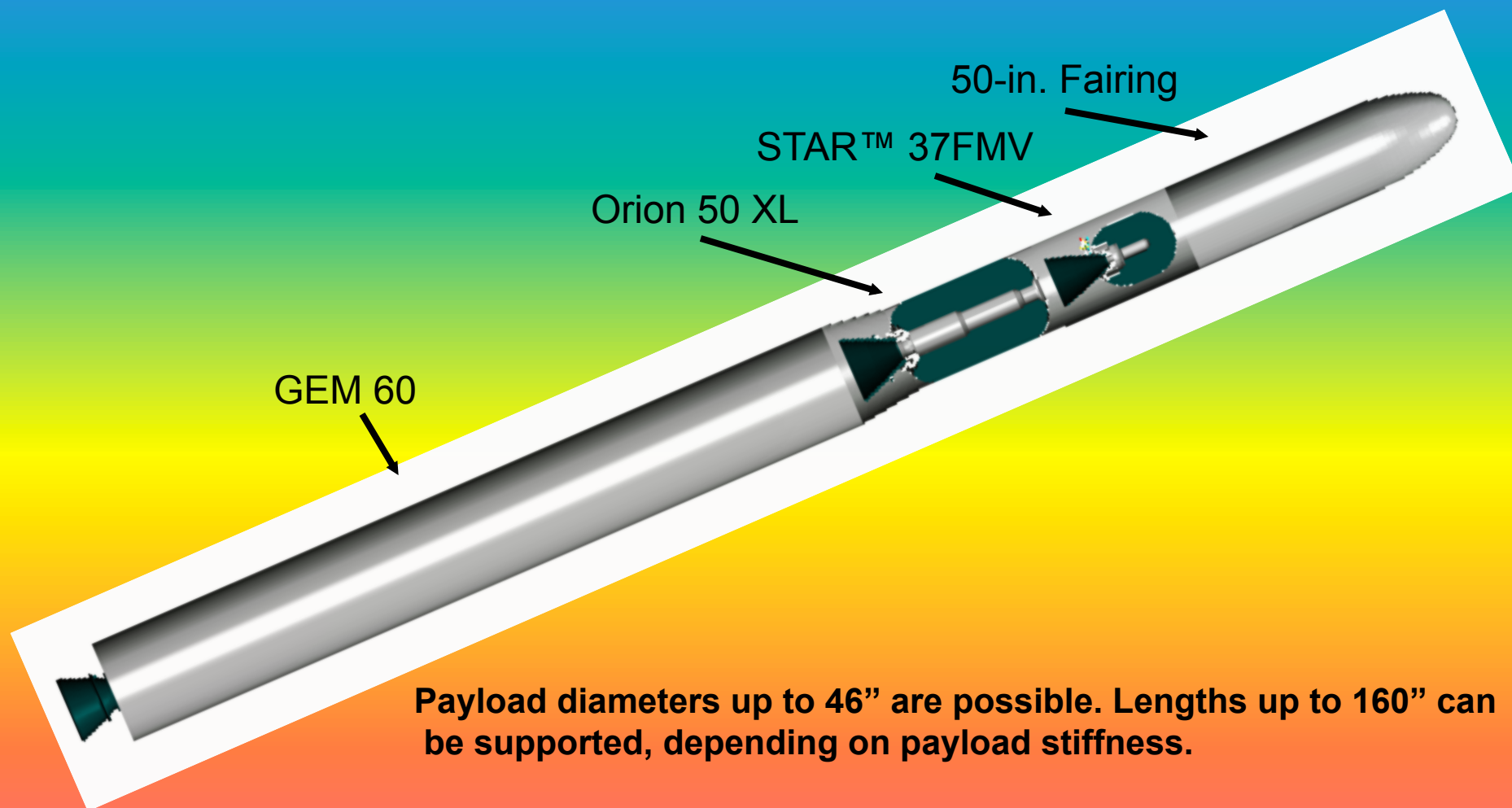
Payload diameters up to 46" are possible. Lengths up to 160" can be supported, depending on payload stiffness.

Fairing may not be necessary for sounding rocket payloads mounted in a structural shell designed to withstand loads incurred during launch, e.g. Black Brant 22-inch diameter skin.
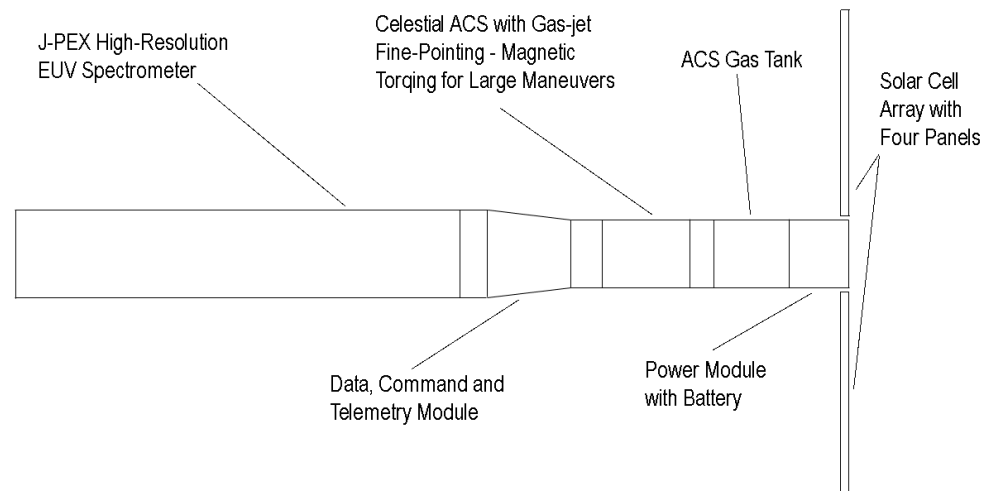
J-PEXsat
STRAWMAN CONFIGURATION AND MISSION

NASA 36.195 payload (2001)

- J-PEX High-Resolution EUV Spectrometer
- Celestial ACS with Gas-jet Fine-Pointing - Magnetic Torqing for Large Maneuvers
- ACS Gas Tank
- Solar Cell Array with Four Panels
- Data, Command and Telemetry Module
- Power Module with Battery

Strawman configuration for an orbital mission

- **3-month mission**
  - **~30 White Dwarf stars**
  - **Observe each target 2 days (576 sounding rockets!)**
- **Payload preparation and vehicle integration at NASA Wallops, eastward launch into LEO**
- **Magnetic torque maneuver to next target**
- **Arcsec pointing system: new Celestial ACS + ST5000 tracker**
- **Fine pointing with gas jets: ACS gas (C_2H_6?) stored as liquid.**
- **Data stored in onboard memory: Dump data to Wallops (S-Band) 2500 kbit/sec in one 100s pass**
- **Power system: solar cell array (600W) with rechargeable battery**
- **Temperature control: multilayer insulation blanket and radiation cooling panels exposed by louvers**

CANDIDATE WHITE DWARFS

EUVE	type	common name	time(ks)	photons	ISM?	comment	EUV	opt
J1316+290	DAw	HZ 43	8	271.0088	ISM	Hot DA 3He measurement	3E+05	12.56
J1257+220	DAw	EG 187	57	23.6436	ISM	Int. temp DA/metals	4148	13.4
J2312+107	DAw	GD 246	400	144.04	ISM	Hot DA/metals	3601	13.11
J0505+528	DAw	G191 B2B	4	1.0344		DA/metals	2586	11.78
J1032+534	DA	RE J1032+532	270	62.694	ISM	Pure H DA	2322	14.5
J2009-604	DA	RE J2009-602	2000	451	ISM	Pure H DA	2255	13.4
J2156-546	DA	RE J2156-543	400	87.24	ISM	Pure H DA	2181	14.3
J0457-281	DA	RE J0457-281	10	1.936		Very hot DA/metals	1936	14
J0053-330	DA	G659	200	35.74	ISM	pure H	1787	13.38
J0552+158	DAw	GD 71	200	30.94	ISM	pure H, low nH	1547	13.06
J2214-493	DA	RE J2214-491	6.7	0.73499		Very hot DA/metals	1097	11.7
J1059+514	DA	LB 01919	2300	233.91	ISM	Pure H DA	1017	16.8
J2112+500	DAw	GD 394	400	39.24	ISM	Int. temp DA/metals	981	13.09
J1236+479	DA	PG 1234+482	560	53.256		Hot DA/metals	951	14.38
J0029-634	DA	RE J0029-632	4000	319.2		DA H/metals	798	15
J2324-547	DA	RE J2324-547	2000	120.2	ISM	Hot DA/metals	601	15
J1847+019	DA	BPM 93487	80	4.616	ISM	Pure H DA	577	12
J1126+186	DAw	PG 1123+189	800	35.6	ISM	Hot DA/metals	445	13.11
J0348-009	DA	GD 50	38	1.634		High mass DA	430	14.05
J0623-376	DA	RE 0623-374	20	0.802		very hot DA/metals	401	12
J2334-472	DA	RE J2334-471	67	2.0636	ISM	Hot DA/metals	308	13.1
J0654-021	DAw	GD80	1700	37.4		Int. temp DA, metals?	220	14.82
J0503-288	DO	RE 0503-285	40	0.308		Hot DO/metals, He rich	77	13.9

EUVE	types	name	time(ks)	photons	ISM	comment	EUV	opt
J0645-167	DA+AIV	Sirius A,B	570	415.929	ISM	nearest WD	7297	8.44
J0515+326	DA+F	HD33959C	260	54.132		DA + F binary	2082	7.95
J0235+037	DA+dM1.5	Feige 24	6.7	0.72427	ISM	DA/metals + dM binary	1081	12.4
J0350+172	WD+k0	V471 Tau	130	9.62		DA+ dK binary	740	9.2
J0134-161	DA+dM	GD 984	1200	81.96		DA+dM binary	683	13.8
J2126+193	DA+A8m	HR 8210	440	27.544		DA + A	626	6.07
J0459-102	DA+K	HR1608	1100	16.39	ISM	DA + K binary	149	5.38

- **Science program**
  - **Survey DA White Dwarfs (isolated and binaries): He, metals (with FUV)**
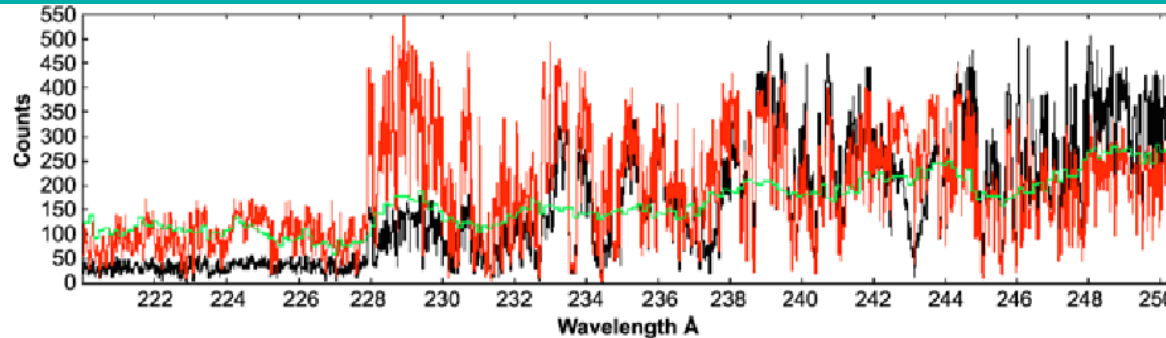 - **Control: "pure" H White Dwarfs**

Figure A. Simulated 4000 sec exposure of the DA WD+dM binary Feige 24, for H layer masses of 10^{-13} (red) and 10^{-14} (black) $M_{\odot}$. The green histogram shows the EUVE observation. Poisson noise has been included, but all fluctuations are real spectral features.
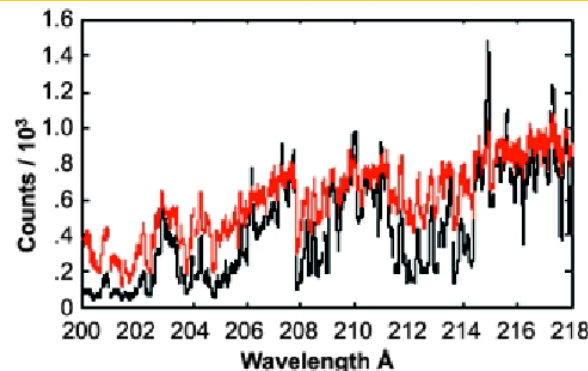

Figure D. Simulated 10 ksec observation of G191-B2B showing the absorption line strengths for a stratified (black) and homogeneous (red) distribution of Fe.

SUMMARY

- **Important Science**
  - **White Dwarfs: End Points of Stellar Evolution**
  - **Interstellar Medium: Sources of Ionization and Heating**
  - **EUV critical window: atomic processes of million-degree plasmas**
- **Need Sensitive High Resolution Spectroscopy**
  - **Spectral Resolution 3500-5100, Effective Area ~7 cm^2**
  - **Multilayer Optics Technology Mature**
- **NASA Programmatics & Cost**
  - **SALMON**
  - **Possible joint mission with DoD**